Ultra-Relativistic Jets in Astrophysics

Observations, Theory & Simulations

Conference summary on AGN / quasar jets

(Mirabel), Gabuzda, Giroletti, Hardcastle, Ghisellini, Gelbord, Pelletier, Perlman, Harris, Hawley, Trussoni, Georganopoulos, Mizuta, Meier, Croston, Laing, Schwartz

Giovannini, Moloney, O'Dowd, Mahmud, Marshall, Padgett

s.a. DeVilliers, Nishikawa, Mizuno, DelZanna, Mac Fadyen (theory) ...

Christian Fendt

Max-Planck Institute for Astronomy

Ultra-Relativistic Jets in Astrophysics

Observations, Theory & Simulations : AGN / quasar jets

Problem setup: to understand formation (acceleration, collimation), launching, dissipation of relativistic jets

--> formation site: accretion disk vs. black hole magnetosphere

(--> Blandford-Payne vs. Blandford-Znajek
--> magnetohydrodynamic vs. electrodynamic)

launch of disk outflow / knot generation

matter content of relativ. jets (hadronic/leptonic)

accretion disk structure / radiation

generation of magnetic field (disk dynamo, MRI)

Michel scaling:

$$\Gamma \sim \sigma^{\alpha}, \ \alpha \simeq \frac{1}{3} \ldots 1, \quad \sigma \sim \frac{\Phi^2 \Omega_F^2}{dM / dt}$$

Ultra-Relativistic Jets in Astrophysics

Observations, Theory & Simulations : AGN / quasar jets

Problem setup: to understand formation (acceleration, collimation), launching & dissipation of relativistic jets

--> jet propagation: asymptotic jet (> kpc … Mpc)

bulk velocity / mass flow rate
magnetic field strength/structure (Poynting dominated?)
interaction with ambient medium
    entrainment / cocoon back flow / bending
dissipation of mag./kin. energy in radiation
radiation processes:
    syncrotron / I-Compton (s-self /ext.)
    re-heating (electrons)
knots / clumpiness

--> unified model of relativistic jets ???

Ultra-Relativistic Jets in Astrophysics

Observations, Theory & Simulations : AGN / quasar jets

Problem setup: to understand formation (acceleration, collimation),
launching & dissipation of relativistic jets

theory:

--> pure MHD models, stationary / simulations:
- geometric preconditions, physical limitations
- small grid (central region), low resolution, (Newtonian code)

GR-MHD simulations (disk evolution, jet launching)

--> density, velocity, field strength

--> HD simulations with rad. transfer, tracer particles/field

--> radio maps, polarization

observations:

--> large scale morphology (l. o. s. integrated intensity, pol I)

--> spectra, radiative energy (radio ... X-ray ... TeV)

--> source variability, modeling radiation processes (theory)

--> field strength, e- temperature, time scales

Ultra-Relativistic Jets in Astrophysics

Observations, Theory & Simulations : AGN / quasar jets

Family of relativistic jets:

AGNs,quasars:

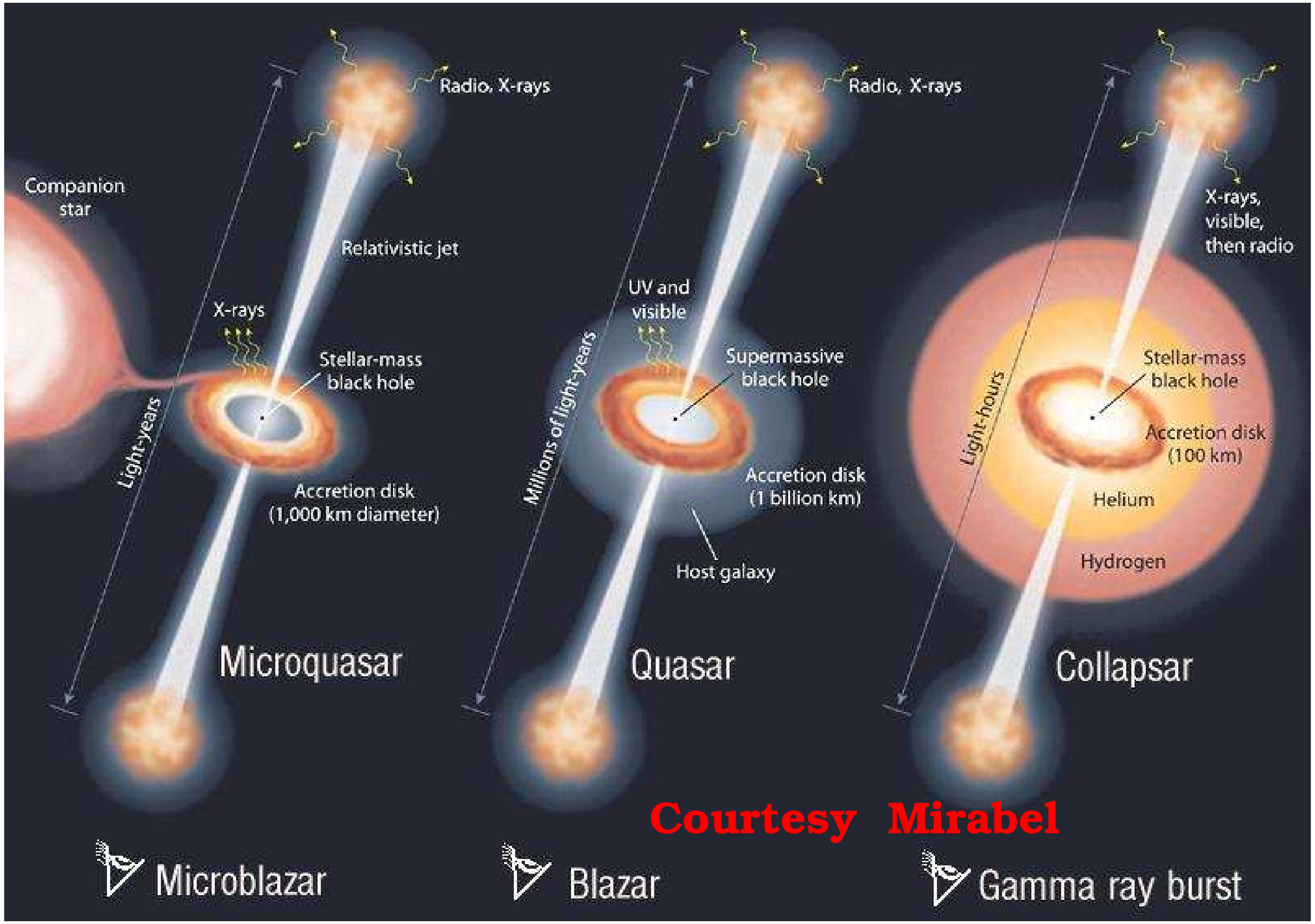
$$L \simeq 10^{43 \ldots 48}\ erg / s$$
$$\Gamma \simeq 10$$

μ -quasars:

$$L \simeq 10^{38 \ldots 40}\ erg / s$$
$$\Gamma \simeq 1 \ldots 10$$

GRBs

$$L \simeq 10^{52}\ erg / s$$
$$\Gamma \simeq 10^{2 \ldots 4}$$



Courtesy Mirabel

Ultra-Relativistic Jets in Astrophysics

Observations, Theory & Simulations : AGN / quasar jets

Family of relativistic jets: AGNs, quasars, μ -quasars, GRBs

--> similar / same jet formation mechanism

--> different length / time / energy scales; scale with BH mass

--> observational window for physical processes

$$\Delta t \sim M_{BH}$$

$$R_S = 2\, G M_{BH} / c^2$$

$$T^4_{col,disk} \sim M / 10\, M_{sun}$$

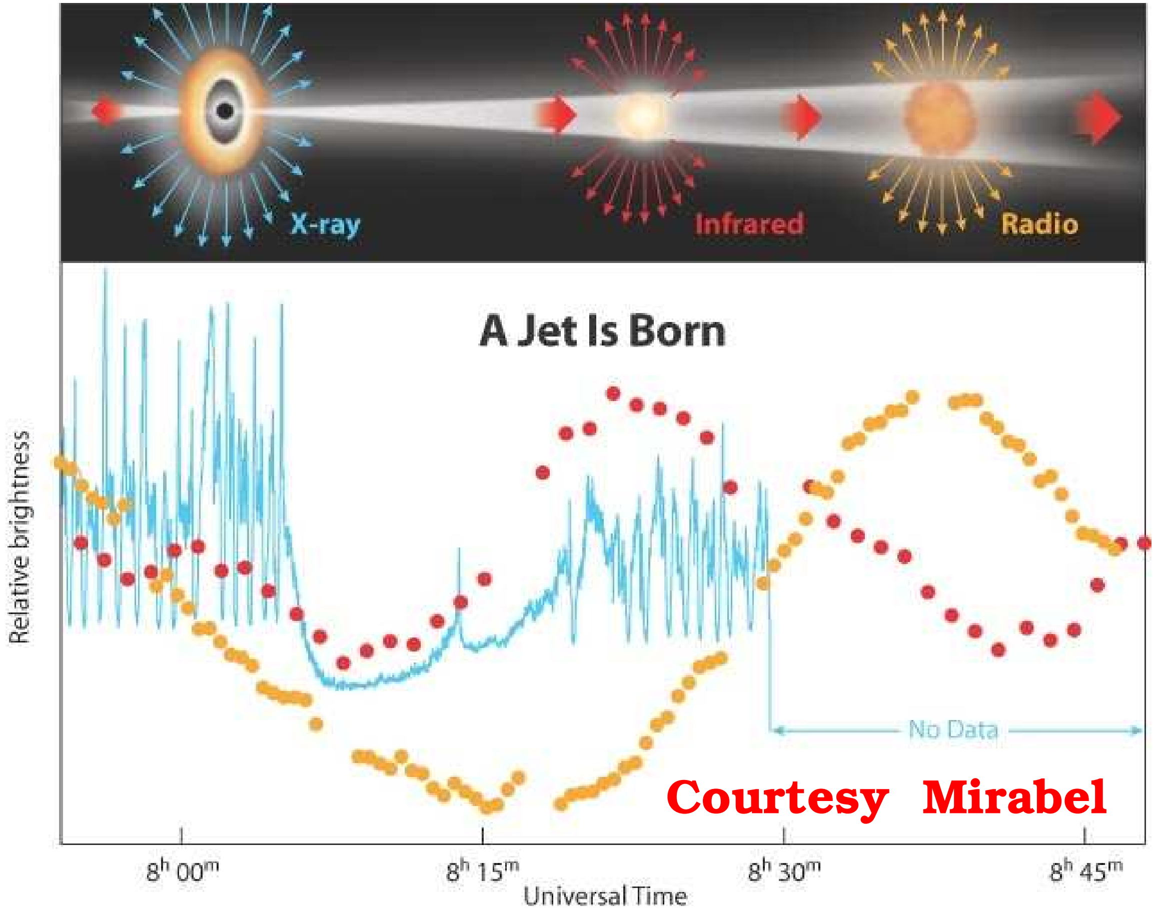
Diversity (given accretion rate):

$$L_{bol} \sim M_{BH}$$

$$l_{jet} \sim M_{BH}$$

$$\theta \sim M_{BH}^{-1}$$

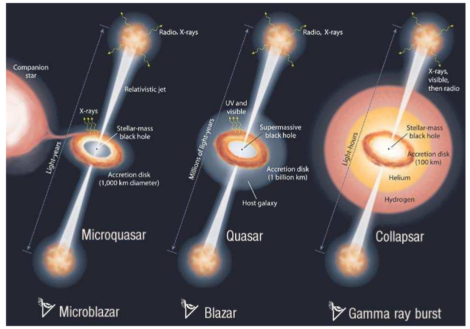
$$B \sim M_{BH}^{-1/2}$$



Ultra-Relativistic Jets in Astrophysics

Observations, Theory & Simulations : AGN / quasar jets

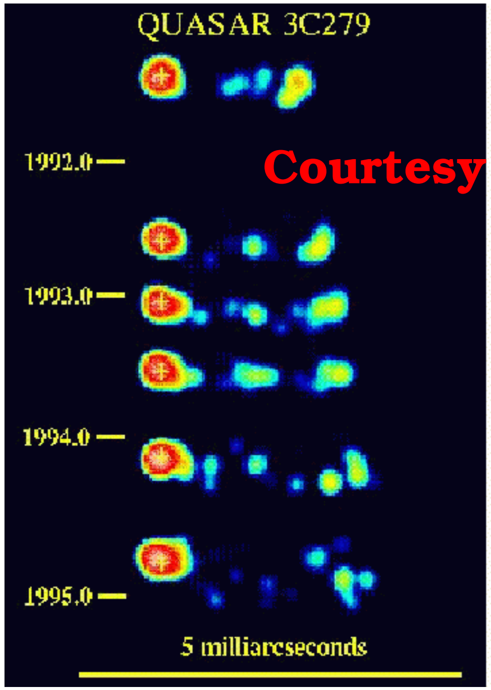
Family of relativistic jets: AGNs, quasars, μ -quasars, GRBs

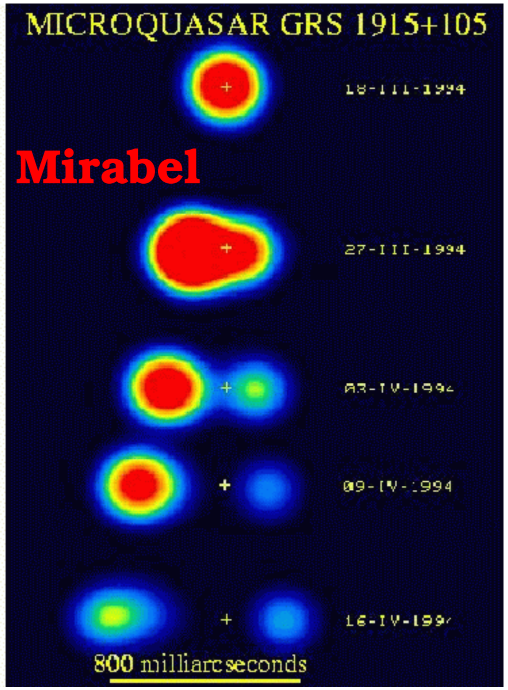


Question: indeed one family ??

--> Possible differences:

- **Binarity** in μ -quasars, none in AGN, ? in GRB
- Stellar mass **BH** is more extrem:
  larger frame-dragging,
  tidal forces, much hotter disk
- **Velocities** partly uncertain
- **NO** confirmed **field structure**
- **Environment**: collapsar - ?
- Observed **degree of collimation:**
  AGNs: cylindrical jets observed
  μ -QSOs: expanding blob
  GRBs: indirect evidence
- **Note nonrelativistic YSO jets**





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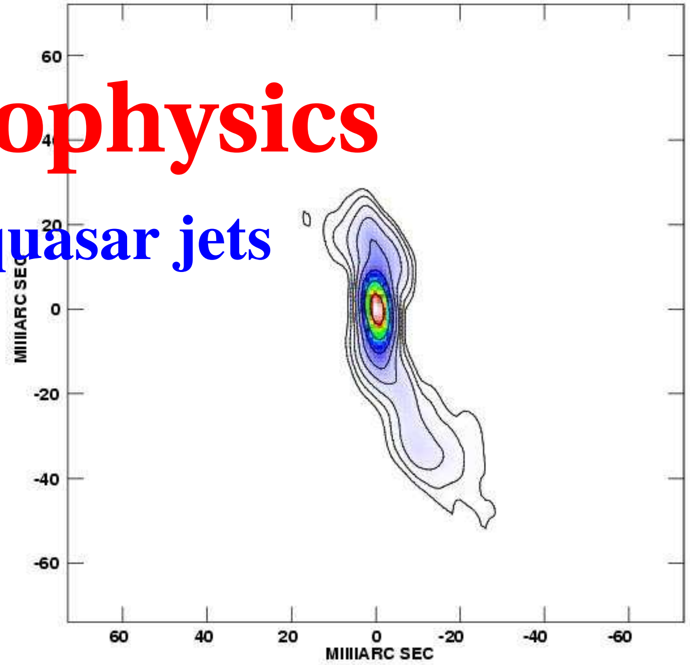
Ultra-Relativistic Jets in Astrophysics

Observations, Theory & Simulations : AGN / quasar jets

Family of relativistic jets:
“m-quasars” (“milli” ?)

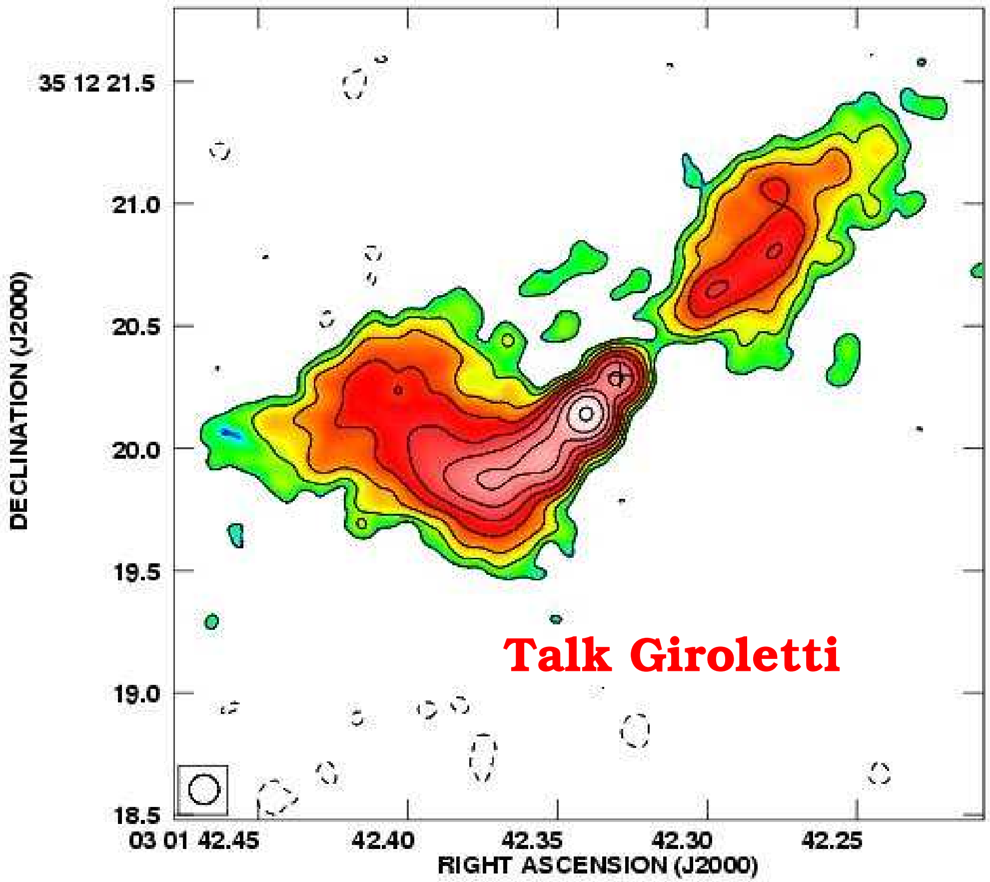


High-resolution VLA & VLBA of
low-power compact radio sources (LPC)

--> resolved sub-structures/jets (#5):
- two-sided, well identfied core,
  FR I, II, down-sized by 100-1000,
- radiative ages $10^{4...5}$ yrs,
  no growth signitures
- confined to galaxies, “small”,
  no kpc-scale radio lobes

--> jets relativistic (?)

--> transition to radio quiet and non-active nuclei (?)



Ultra-Relativistic Jets in Astrophysics

Observations, Theory & Simulations : AGN / quasar jets

X-ray surveys of lobes and jets

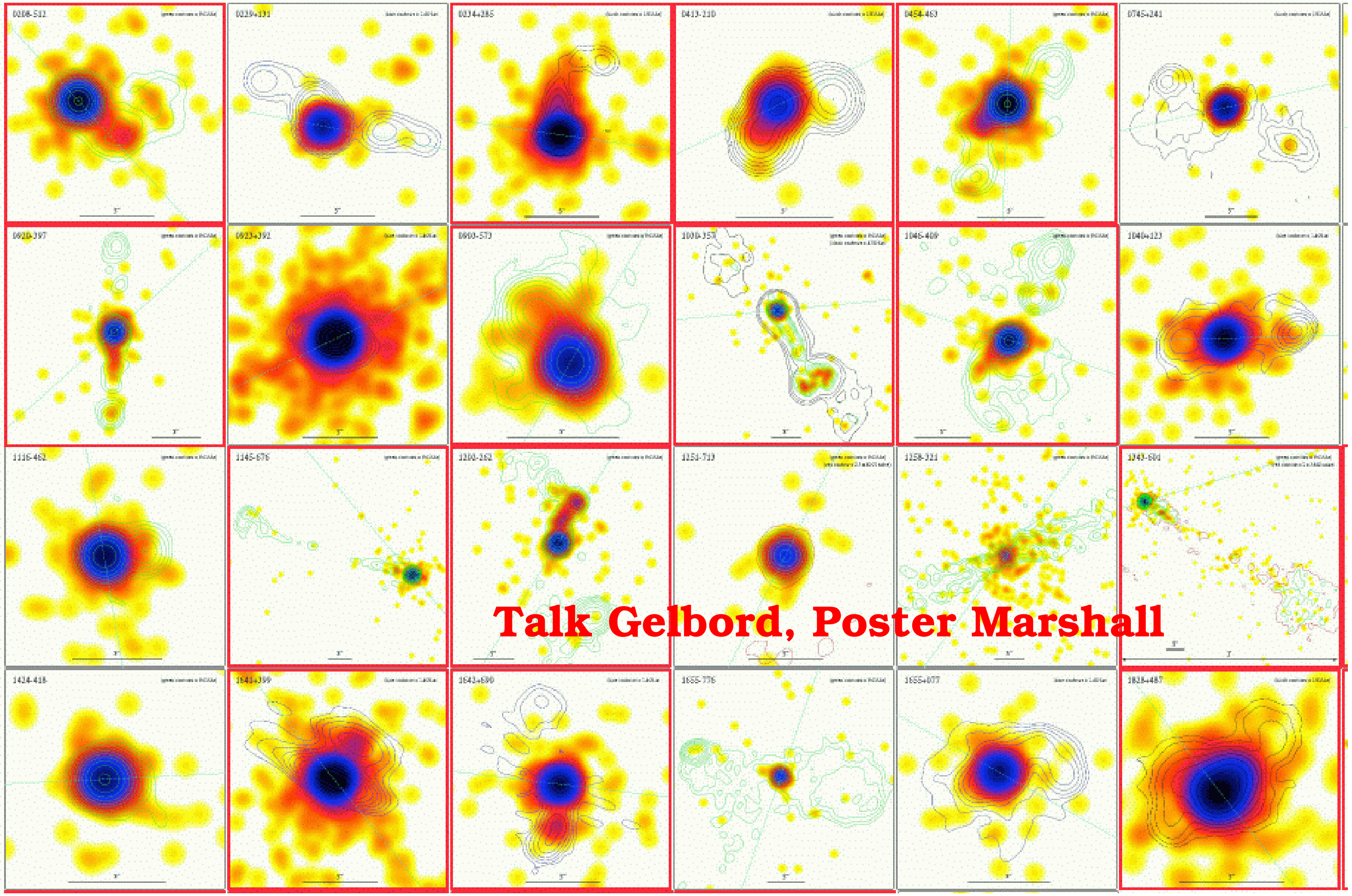
X-ray survey of quasar jets (Chandra, optical follow up)

redshifts: 0.5-2.0

~63 % with X-jet

all with flat
spectrum cores

X-ray consistent
with IC/CMB



Ultra-Relativistic Jets in Astrophysics

Observations, Theory & Simulations : AGN / quasar jets

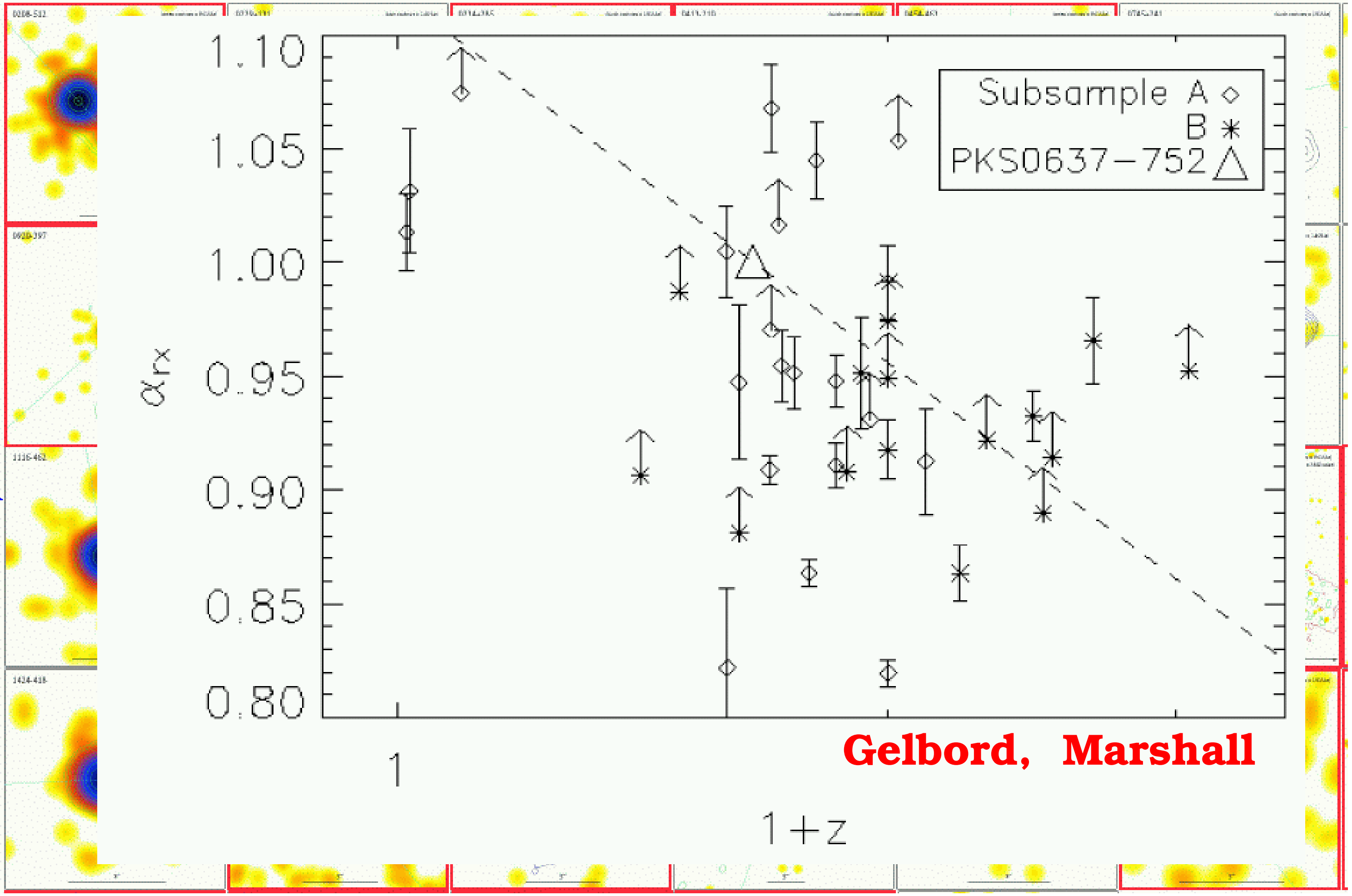
X-ray surveys of lobes and jets

X-ray survey of quasar jets (Chandra, optical follow up)

redshifts: 0.5-2.0

--> spectral index r-X against redshift for IC/CMB models (dashed: normalized to PKS, i.e. X-flux ~ (1+z)^4

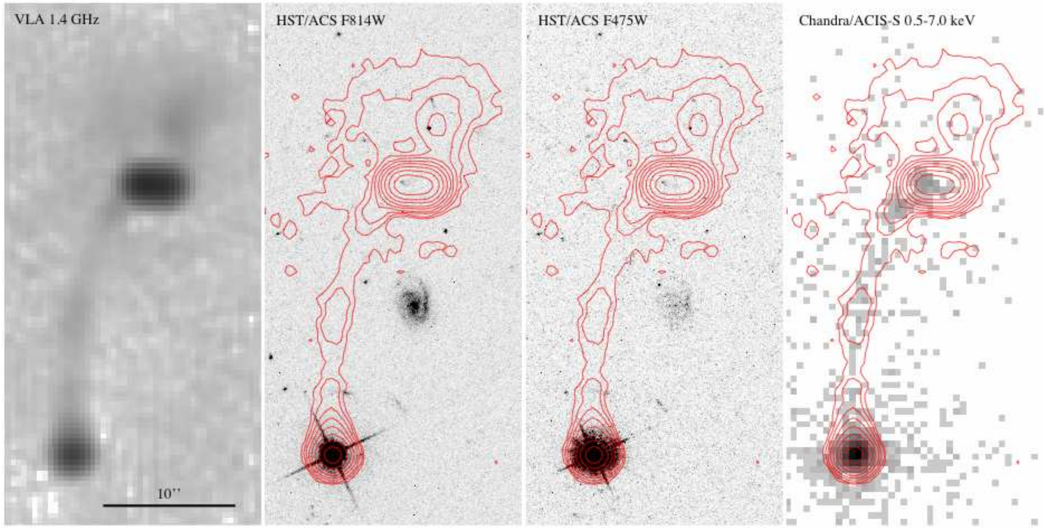
--> wide scatter: variation of beaming paras (Lorentz factor alignment)



Ultra-Relativistic Jets in Astrophysics

Observations, Theory & Simulations : AGN / quasar jets

X-ray surveys of lobes & jets

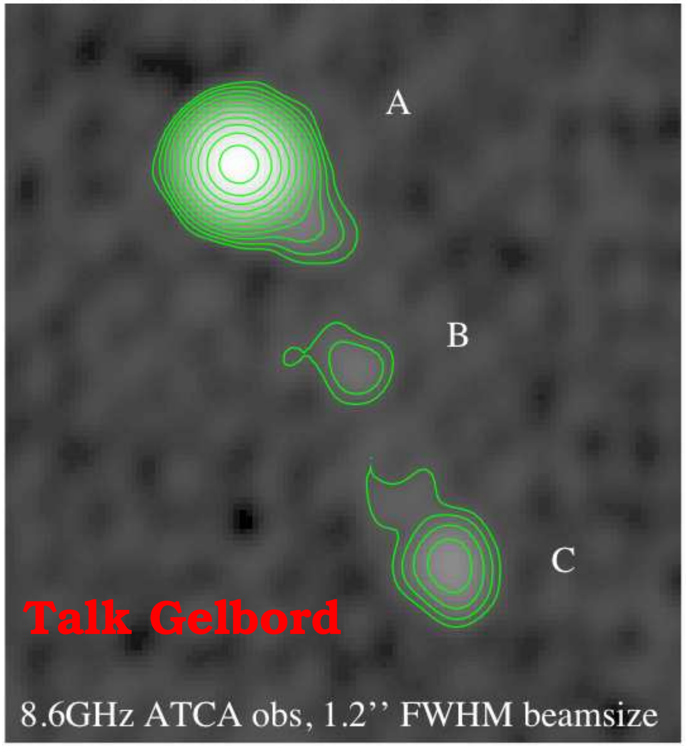


X-ray survey of quasar jets
(Chandra, optical follow up):

Particularly interesting targets:

PKS 1055+201:
- radio & X jets agree
- jet heat ambient medium
- IC/CMB evidence: radio fades
faster than X-ray, B~10 μG, δ=6, θ=9 deg

PKS 1421-490:
- strong radio source, A -> A1, A2
- optical B/A flux ratio ~300
- B optically dominated (factor 5)
- B-A interknot X emission
-> jet / core geometry mysterious



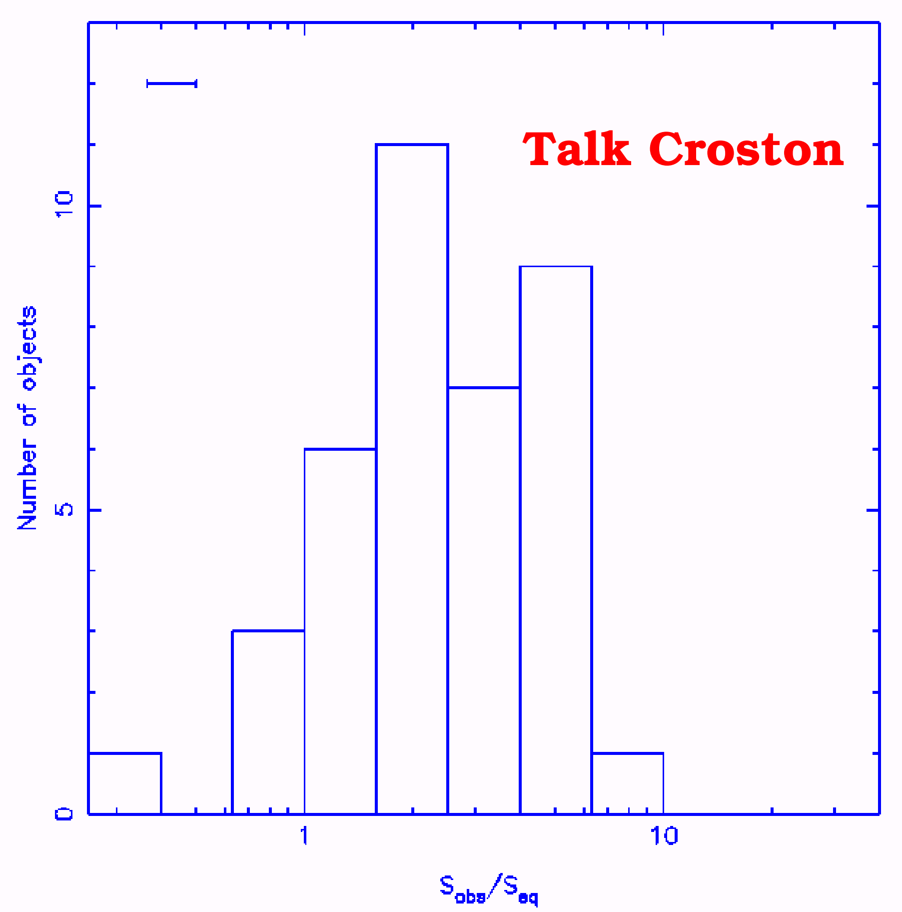
Ultra-Relativistic Jets in Astrophysics

Observations, Theory & Simulations : AGN / quasar jets

X-ray surveys of lobes and jets

X-ray IC emission from radio galaxy & quasar lobes (Chandra & XMM, #33)

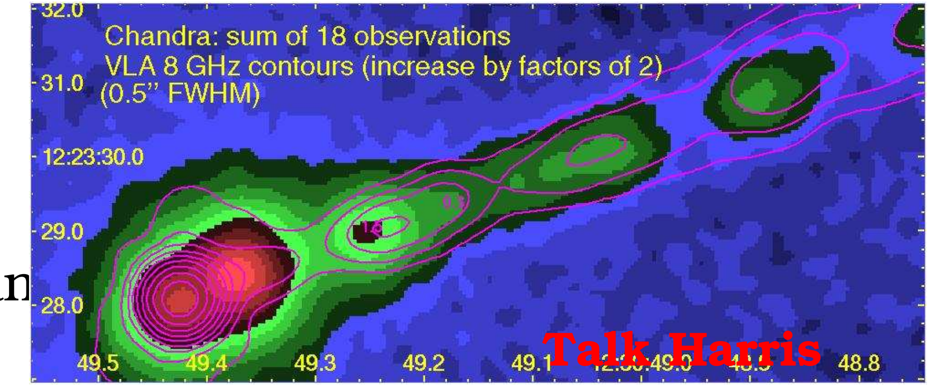
-> first integrated X-ray properties of FR II radio lobes
75% of lobes are X-detected
-> measure of field strength: close to equipartition
-> relativistic protons energetically not important
-> total internal energy of typical radio galaxies ~ 2x minimum
-> complex structure of radio & X-ray emitting regions suggesting a variation of low energy electron population & magnetic field (s. PicA



Ultra-Relativistic Jets in Astrophysics

Observations, Theory & Simulations : AGN / quasar jets

X-ray surveys of lobes and jets: IC/CMB emission



Arguments:

energy densities of B and CMB photons
broadband SED: optical upper limits
low energy electrons furthest downstream
IC-CMB offsets: radio upstream of X
(vice versa in syncrotron: M87)

Implications:

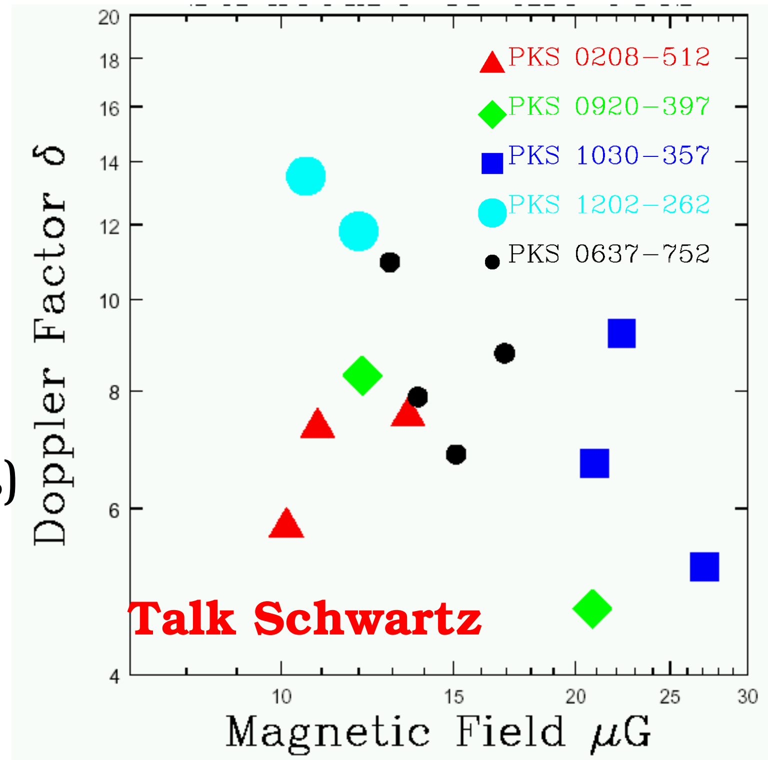
gives B, δ, n_e, kinetic flux,
IC-CMB jets have constant X surface
brightness with z -> observable at high z

Predictions:

to detect Gamma-ray jets,
X-flux dominates jet at large z (more X jets)

Critique:

size of X-knots < optical, radio ?
(and more, see Harris´ talk)



Ultra-Relativistic Jets in Astrophysics

Observations, Theory & Simulations : AGN / quasar jets

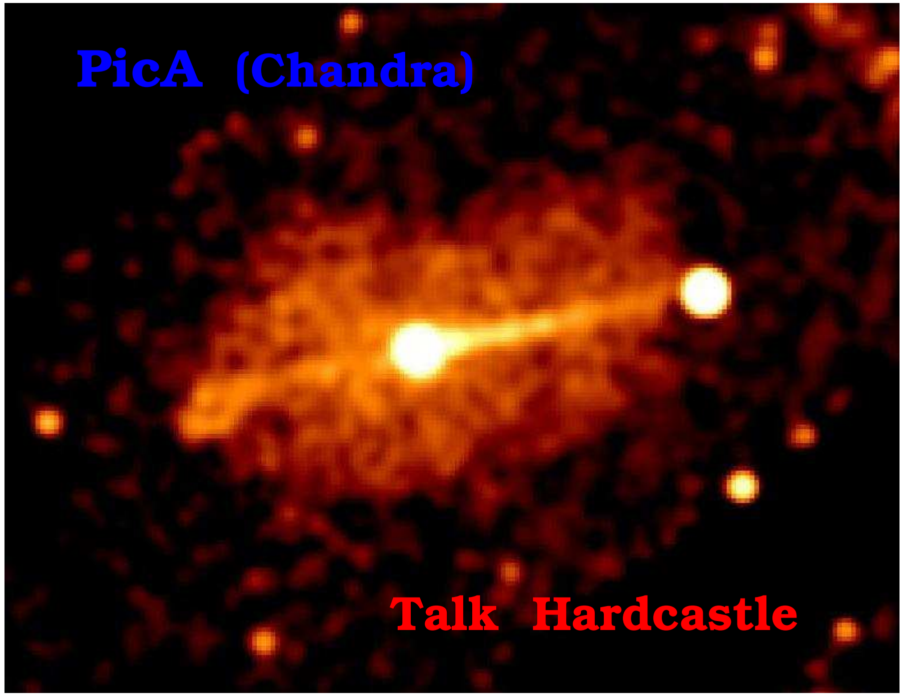
X-ray emission & kpc jet velocities

--> in core-dominated quasars:
discrepancy between
radio data (mildly relativistic jets) and
X-ray data (highly relativistic speed)

--> X-rays by inverse-Compton of CMB
requires $\Gamma \simeq 10 \,..\, 20$

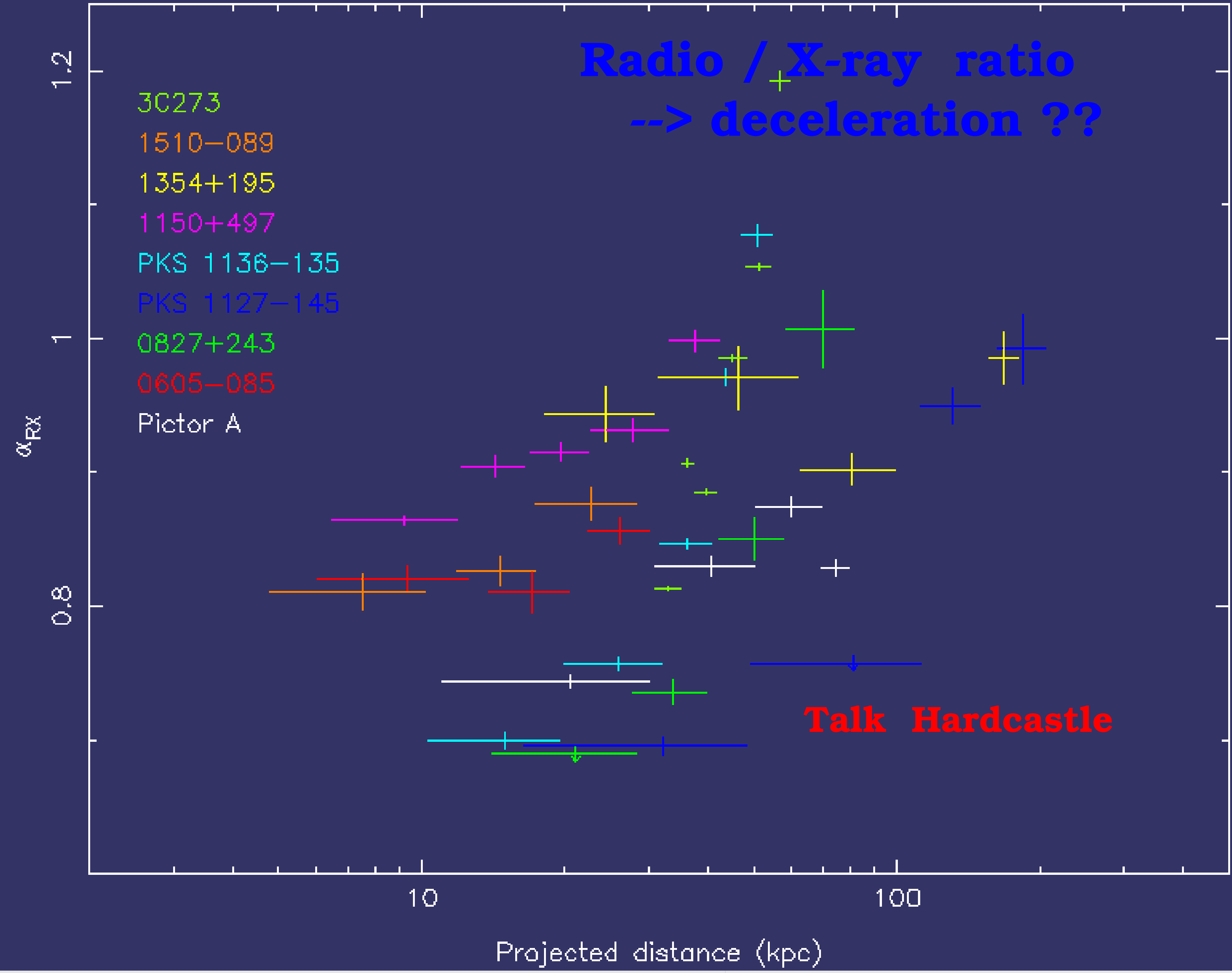
--> if IC/CMB produced X-rays:
- jet velocity structure required:
  slow sheath, fast spine
- spine deceleration on kpc scale

--> syncrotron models for X-ray:
- second syncrotron component
  (as e.g. in 3C 273)
- would unify FR I and FR II
- would explain varying radio/X ratio without deceleration



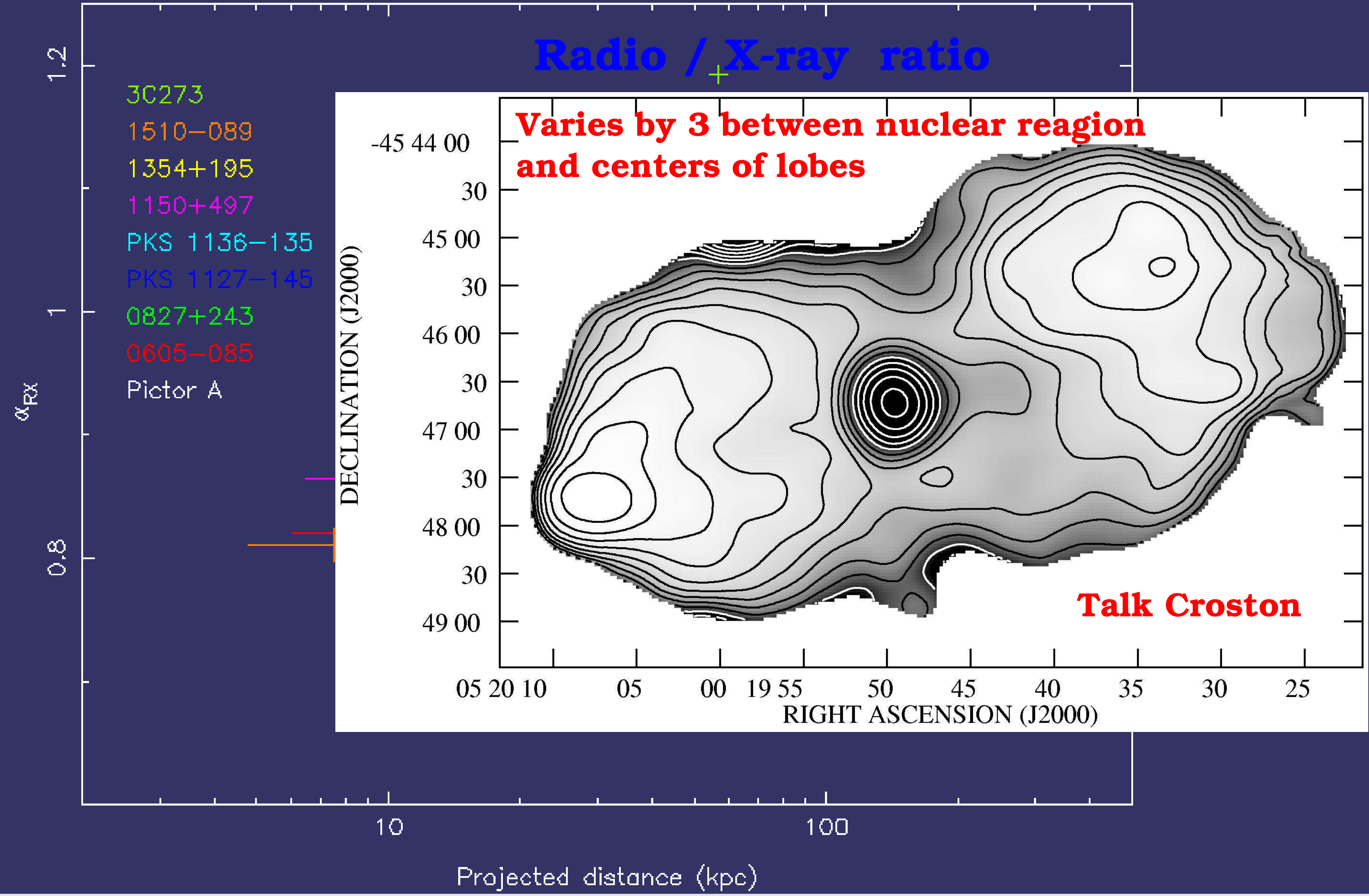
Ultra-Relativistic Jets in Astrophysics

Observations, Theory & Simulations : AGN / quasar jets



Ultra-Relativistic Jets in Astrophysics

Observations, Theory & Simulations : AGN / quasar jets



Ultra-Relativistic Jets in Astrophysics

Observations, Theory & Simulations : AGN / quasar jets

High energy radiation from AGN: M87 as new TeV source

Talks Perlman

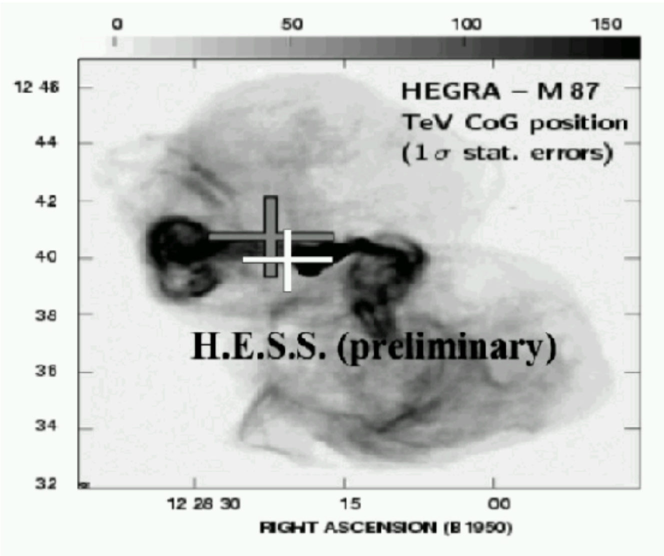
Where does the TeV come from?

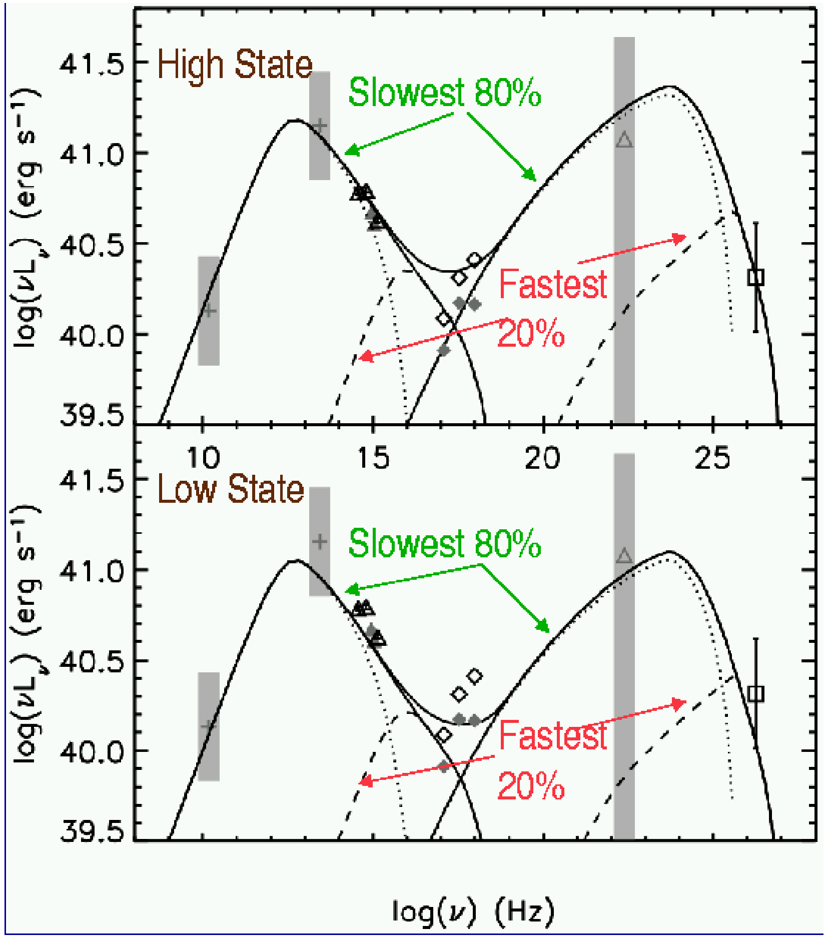
-> nucleus (HST1, knot A ruled out)

-> model fits with decelerating jet: Γ 20 –> 5

-> TeV is upstream compton (UC) emission, higher energy electrons in fast part, cool radiatively as advect downstream

Variability observed (?)





Where does blazar GeVs come from?

--> New powerful code (Georganopoulos etal)

Ultra-Relativistic Jets in Astrophysics

Observations, Theory & Simulations : AGN / quasar jets

Modeling of jet formation / propagation:

Substantial progress during the last years due to GR-MHD simulations of disk-jet interrelation

--> codes may treat $\Gamma < 50$, small β , tens of Keplerian rotations, hundreds of Schwarzschild radii

--> several groups/numerical codes available (ideal for testing/credibility)

--> follow time-dependent evolution of BH disks, outflows observed with relativistic speed

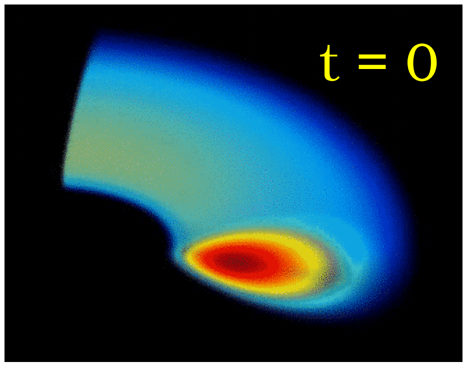
Ultra-Relativistic Jets in Astrophysics

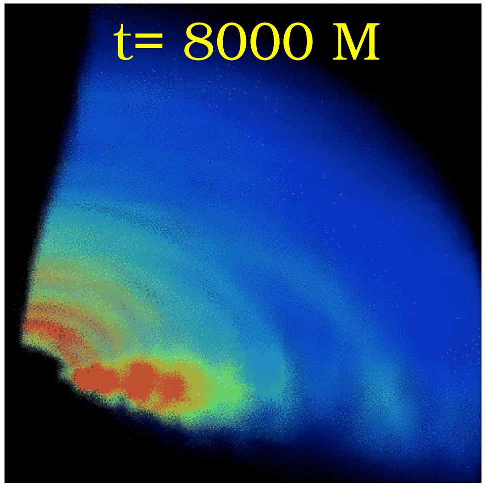
Observations, Theory & Simulations : AGN / quasar jets

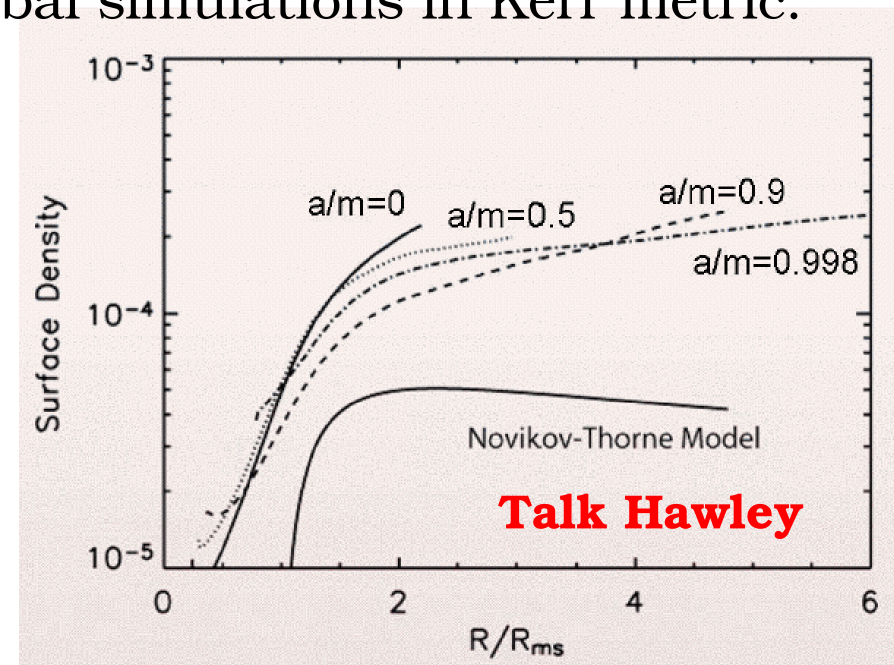
Modeling of jet formation / propagation:

Questions adressed by GR-MHD simulations:
- disk structure – instabilities – turbulence – field generation - jet launching – BH spin effect on accretion – accretion effect on BH -

Approaches: local --> global simulations:
- shearing boxes - cylindrical disks - axisymmetric global - 3D global, Newtonian, pseudo-Newtonian - global simulations in Kerr metric:







Ultra-Relativistic Jets in Astrophysics

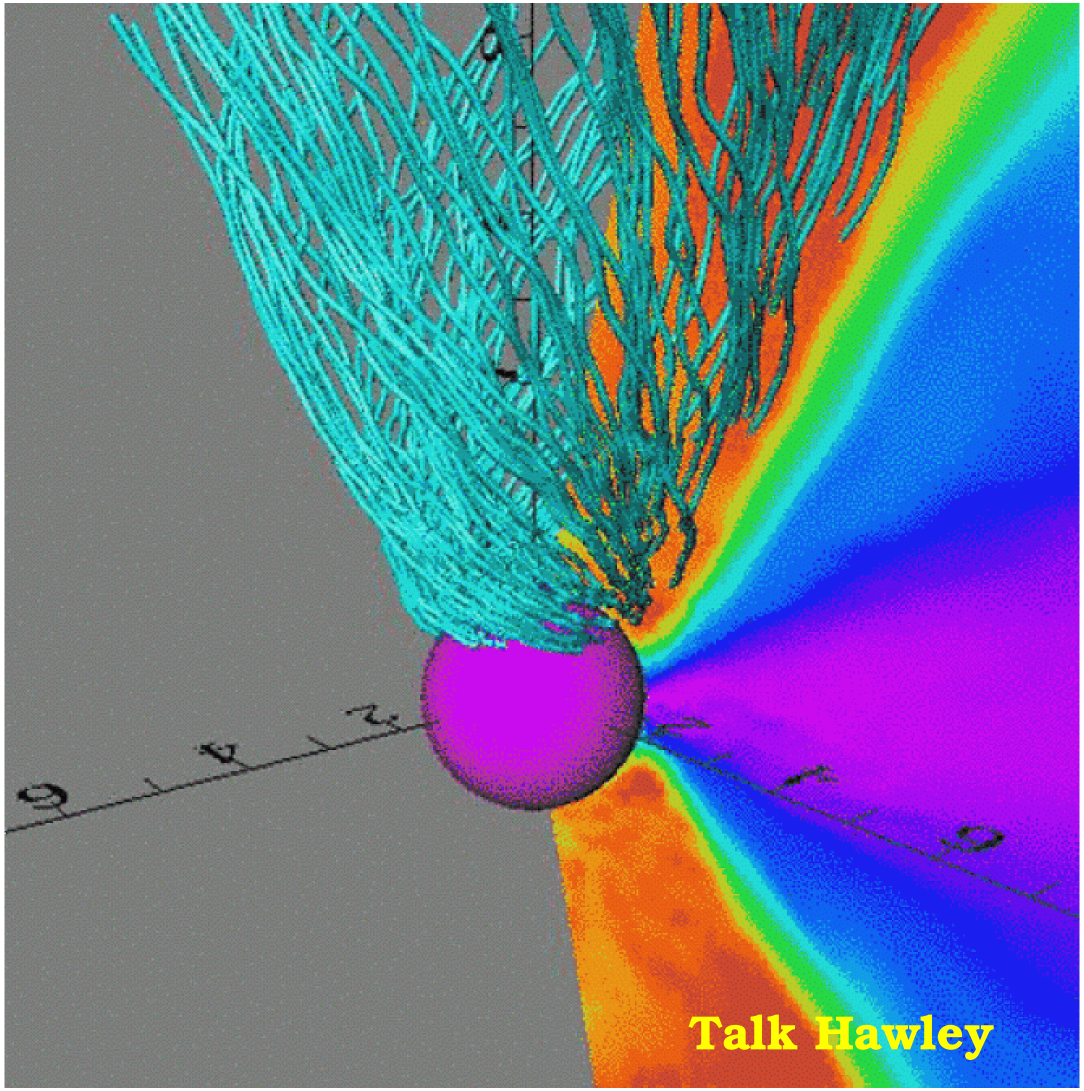
Observations, Theory & Simulations : AGN / quasar jets

Modeling of jet formation / propagation:

Jet formation: combination of rotation, accretion, magnetic field

-> geometry of funnel jets embedded in disk wind:

- axial funnel evacuated, ouflow through funnel,
- mass flux along funnel walls, v~0.4 – 0.6 c
- funnel Poynting flux dominated
- BH spin increases jet power
- pressure and Lorentz force accelerate jet



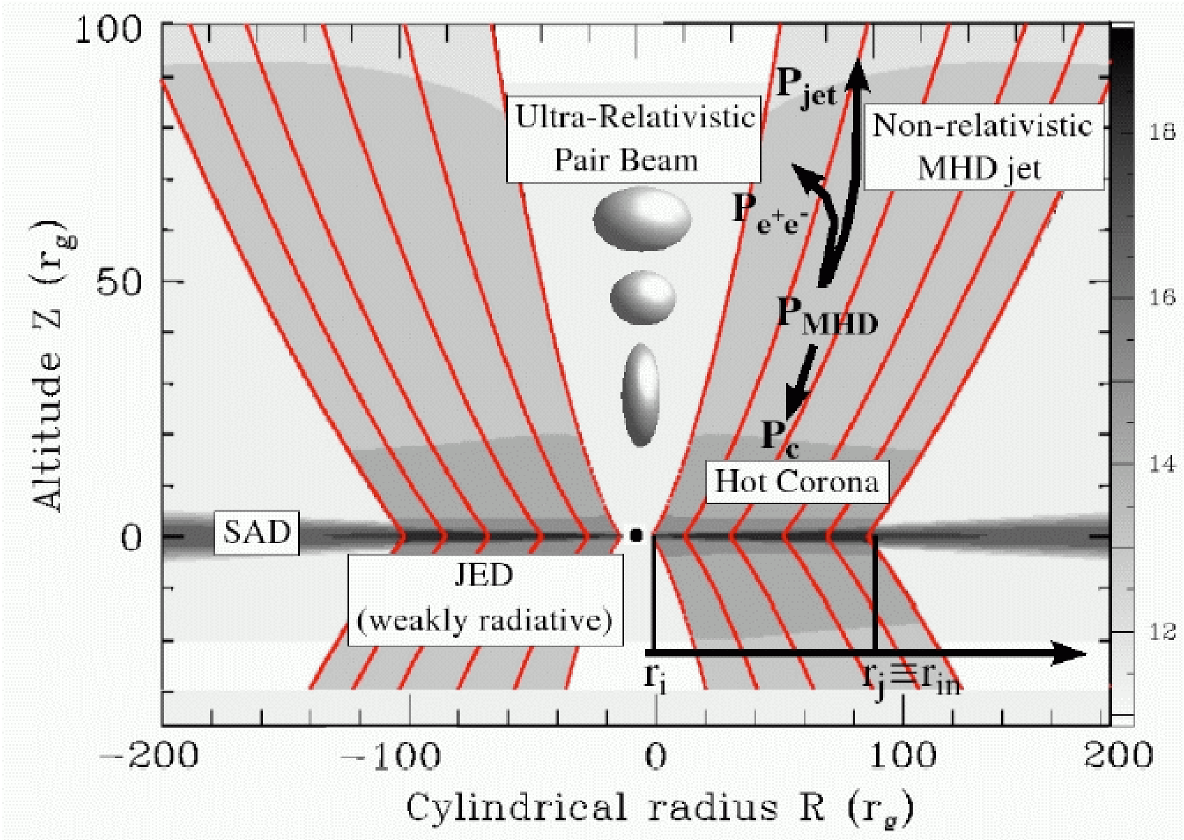
Ultra-Relativistic Jets in Astrophysics

Observations, Theory & Simulations : AGN / quasar jets

Modeling of jet formation / propagation:

Funnel jet <--> "Two-flow model" by Pelletier et al:

- channeling of relativistic jet by ambient subrel. Jet
- problem of relativistic jet self-collimation: strong E
- power in large scale jet
- relativistic reconnection: efficient Poynting flux conversion
- Compton pressure gradient in funnel jet
- Problem pair creation: will kill EM generation of relativistic jet in Blazars



Talk Pelletier

Ultra-Relativistic Jets in Astrophysics

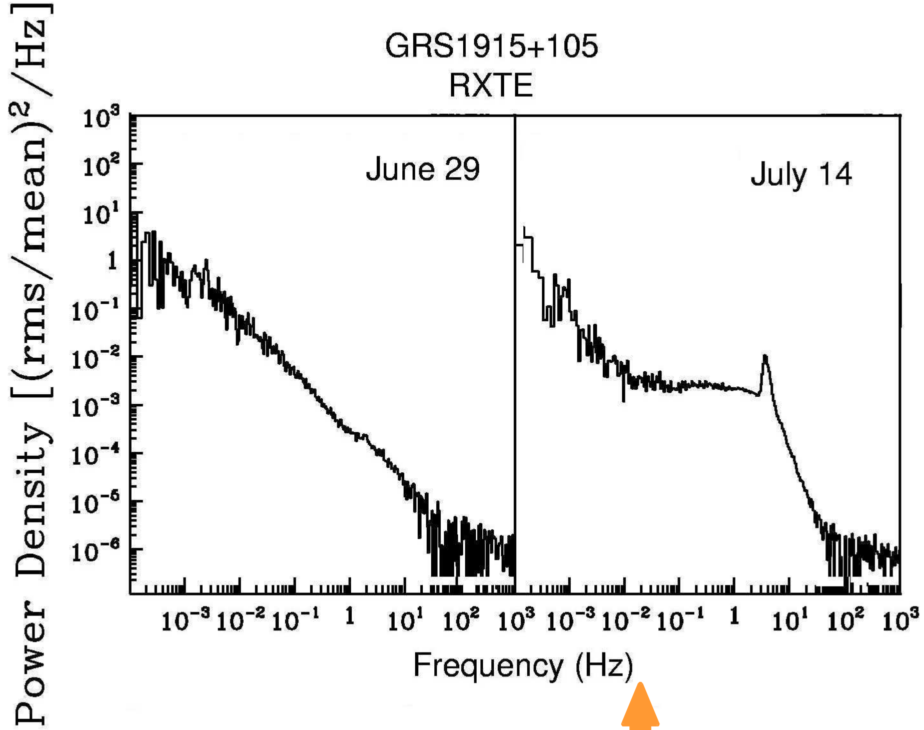
Observations, Theory & Simulations : AGN / quasar jets

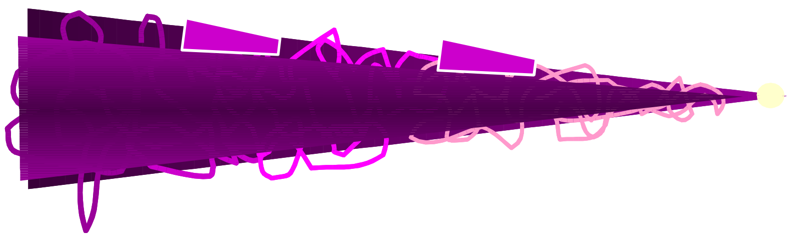
Modeling of jet formation / propagation:

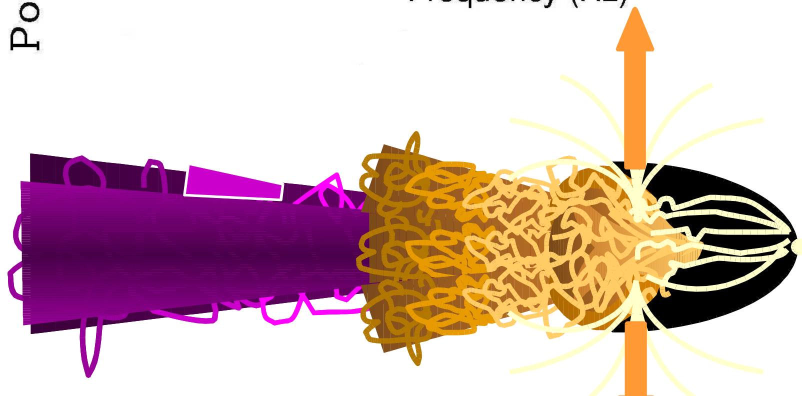
Alternative model of BH accretion disk:

Inner accretion disk magn. dominated
-> **MDAF:** B~r^.5, T~r^.5
(ADAF: B~r^.5, T~r^.5)
Intended to explain activity states in
μ-quasars, QPO signatures,
jet formation at plateau state
ADAF-MDAF transition at ~100 R_H

--> GR-MHD simulations on their way







Talk Meier

Ultra-Relativistic Jets in Astrophysics

Observations, Theory & Simulations : AGN / quasar jets

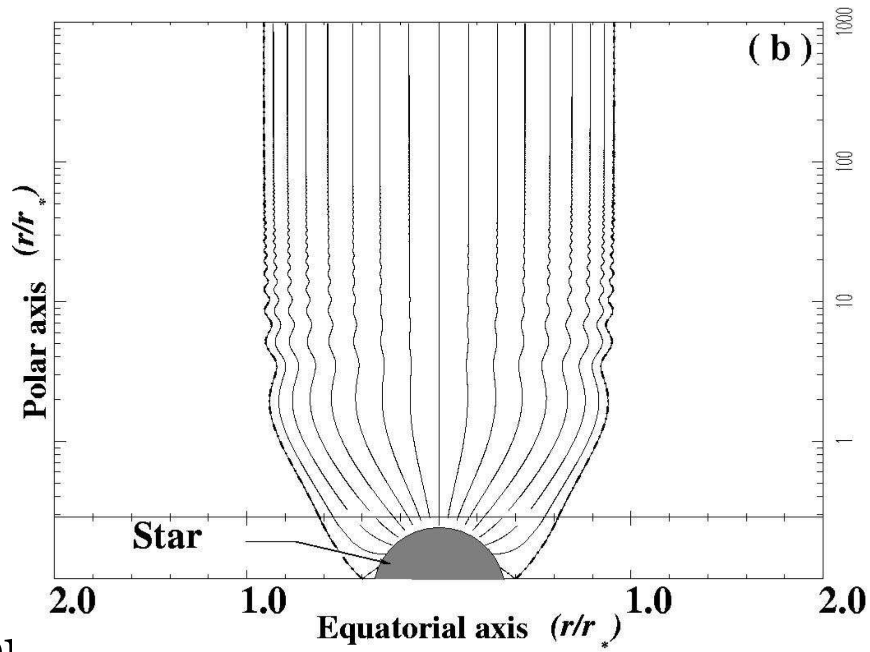
Modeling of jet formation / propagation:

Stationary approach still valuable as
- not limited by computer power: time & spatial resolution:
  jets are huge, strong gradients
- may treat cold very low plasma β jets

--> ansatz: self-similar separation of
MHD equations: $A(r, \theta) = f(r)\ g(\theta)$
e.g. f(r) ~ r^α OR g(θ) ~sin^2θ
--> PDE --> ordinary DE

--> difficulty: singular (magnetosonic) surfaces

--> efficient rotators: magn collimation
inefficient rotators: thermal collimation



Talk Trussoni

Note: time-dependent evolution of stationary solutions ?
Kerr & special relativity not self-similar !!
(first truly 3D-axisym. Kerr-MHD jet solution, Fendt 1997)

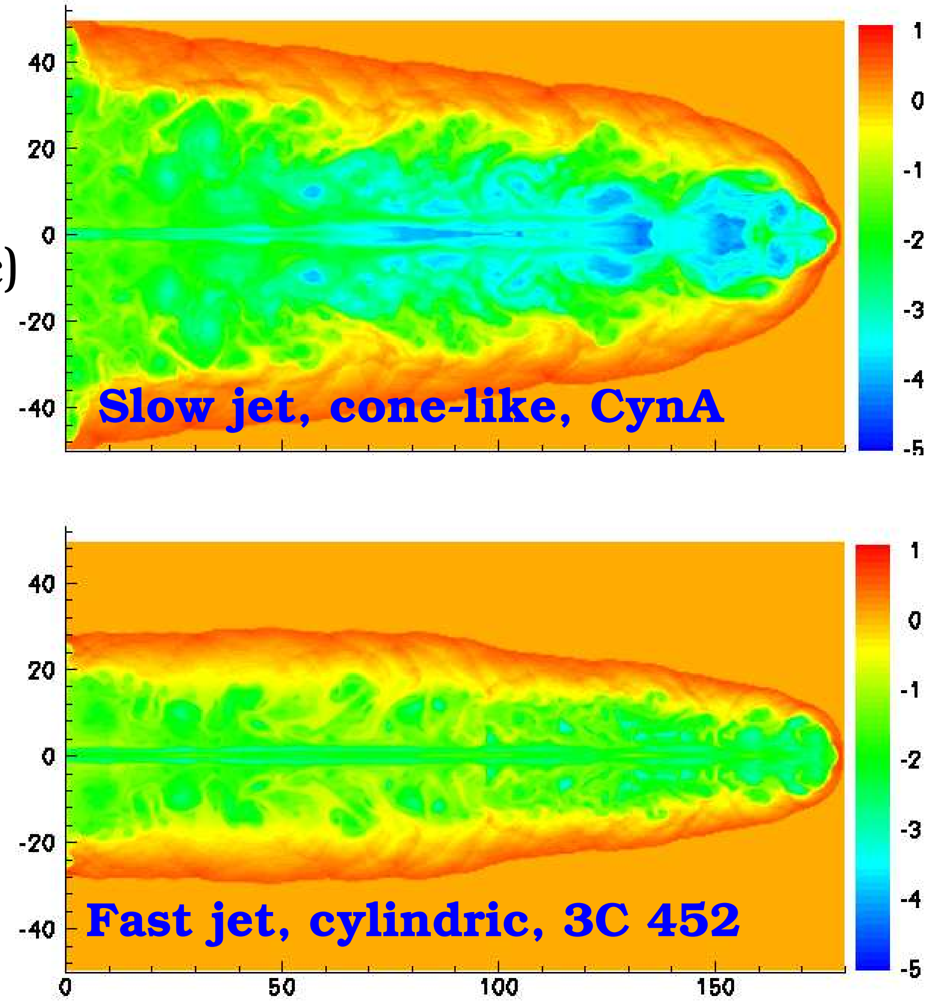
Ultra-Relativistic Jets in Astrophysics

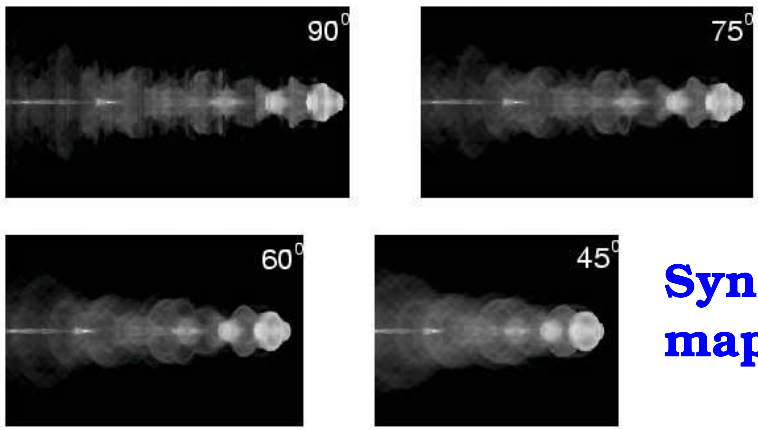
Observations, Theory & Simulations : AGN / quasar jets

Kpc jet dynamics in numerical simulations

- jet dynamics controlled by invisible thermal gas (observed is non-thermal synrotron and IC)
- parameter: density ratio (< .01),speed (c) Mach number (6), head (0.2..0.4c)

-> slow, lighter jets efficiently decelerate
-> third flow along jet axis
-> vortices lead to extended emissivity
-> backflow 0.4c





Syncrotron map slow jet

Talk Mizuta

Ultra-Relativistic Jets in Astrophysics

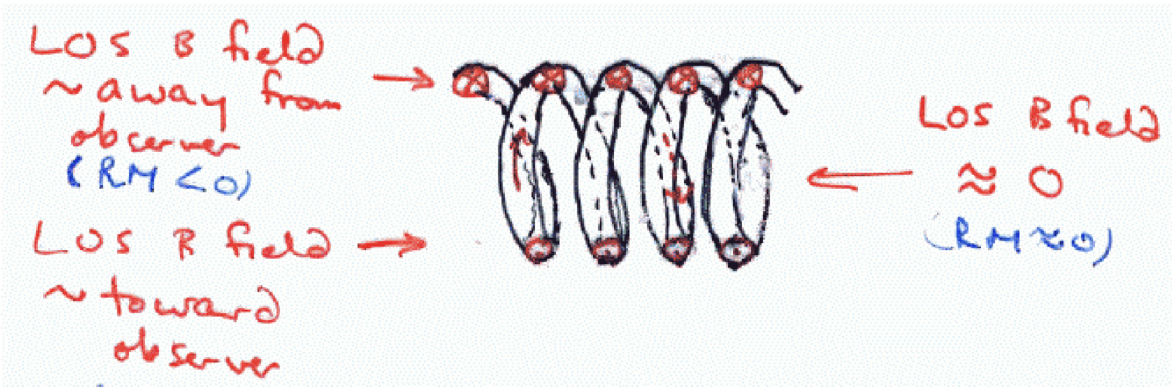
Observations, Theory & Simulations : AGN / quasar jets

Modeling of jet formation / observational input:

MHD models deliver densities, velocities --- Observers see radiation

Major input for modeling: magnetic field strength/structure (mass flow rate)

--> Obervational input from radio polarisation measurements:



Rotation measure (RM)
profile:
- depends ~ pitch angle
- depends ~ viewing angle

--> RM gradient across jet

Talk, posters Gabuzda et al , Poster Lyutikov, Padgett

Ultra-Relativistic Jets in Astrophysics

Observations, Theory & Simulations : AGN / quasar jets

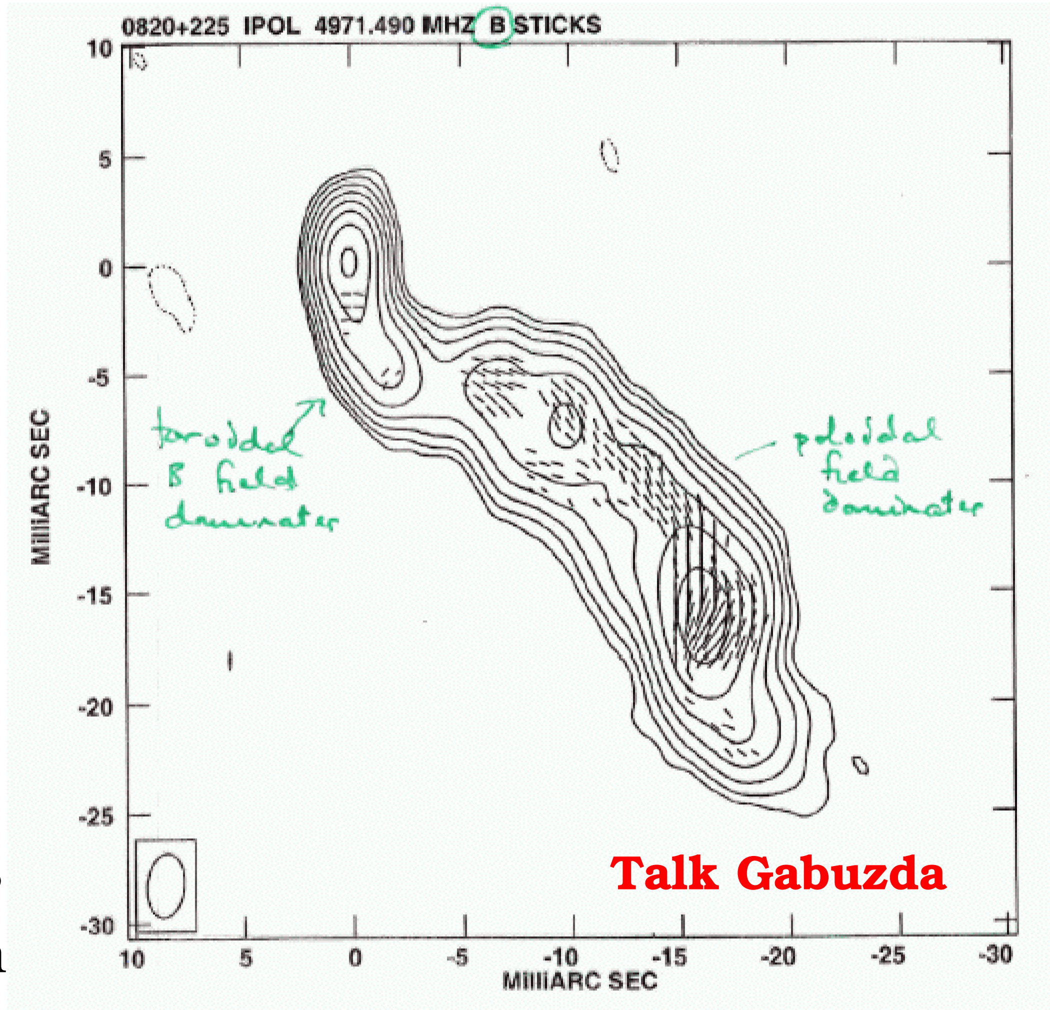
Modeling of jet formation / observational input:

--> toroidal/helical jet magnetic field exists, even dominates (naturally expected from jet MHD modelling)

--> observational proof of jet self-collimation (?)

Further findings:

- circular polarization in some VLBI cores
- RM gradient in AGN cores
  RM_qso < RM_bllac
  --> optical em line differences ?
- optical polarization aligned with VLBI polarization (10-20 deg)



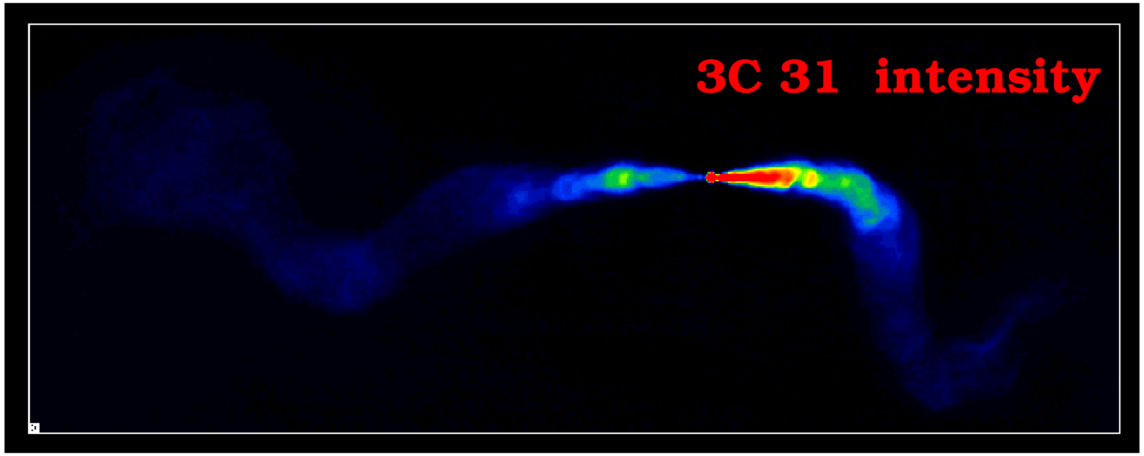
Ultra-Relativistic Jets in Astrophysics

Observations, Theory & Simulations : AGN / quasar jets

Modeling extended jets: quantitative FR 1 models

FR1 decelerating relativistic flows
("free models")

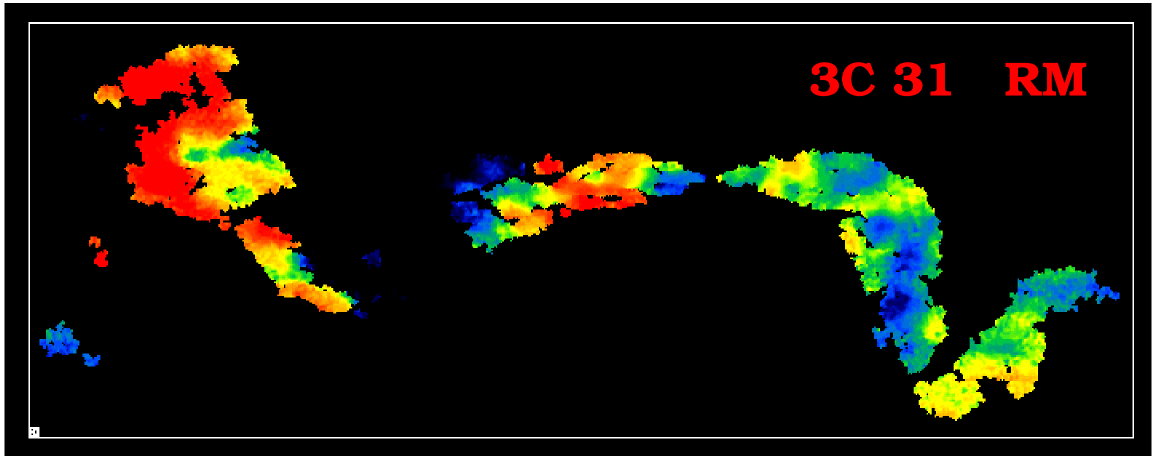
- 3D distribution of velocity,
  emissivity, field:
  --> radio images
  (intensity, polarizn)



- conservation laws
  -> density, pressure variation,
  entrainment rate along jet

- adiabatic models don't work

- particle injection in fast jet



Talk Laing

Ultra-Relativistic Jets in Astrophysics

Observations, Theory & Simulations : AGN / quasar jets

Modeling of jet formation / observational input:

--> matter content of AGN jets /
energy carriers

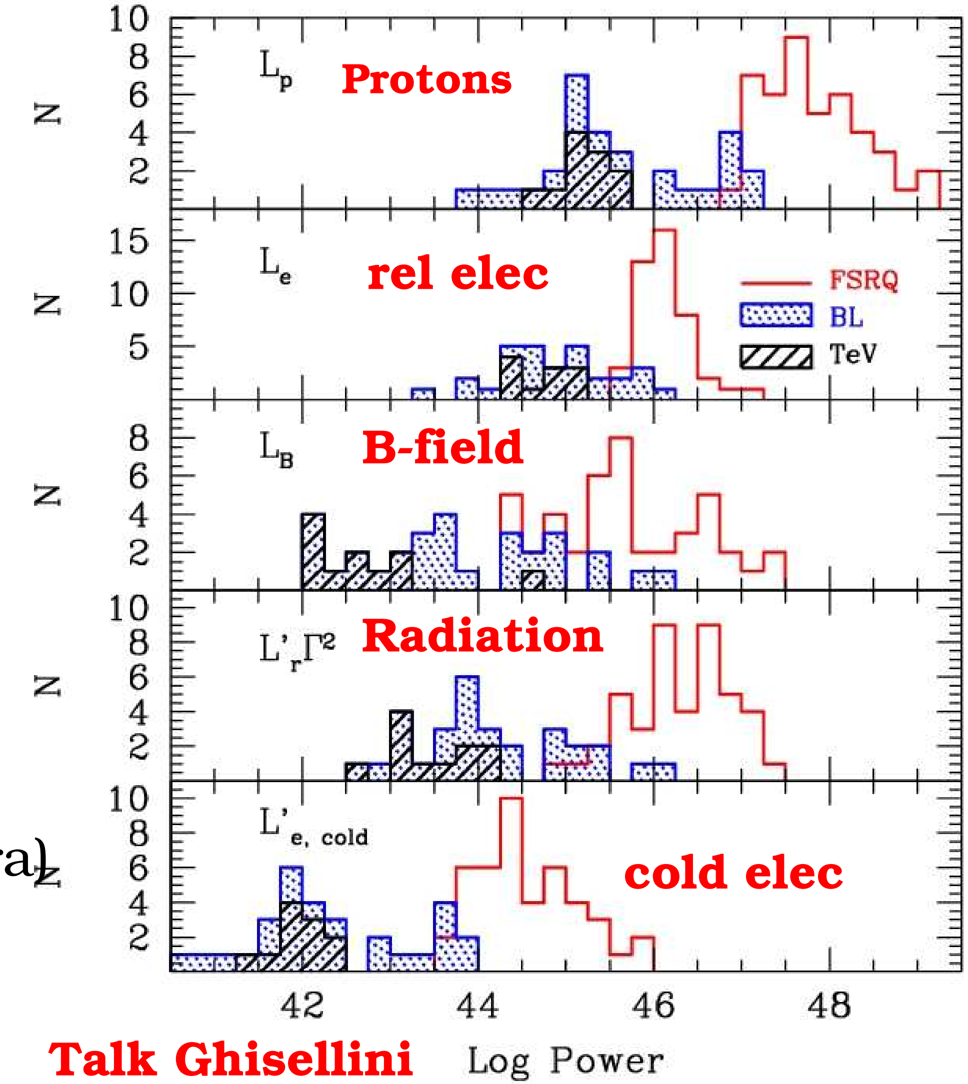
- pairs may outnumber protons
  (but dynamically unimportant)

- L_IC to L_syn large: favors protons

- no sign of bulk compton

- if jet matter dominated & fast from the beginning, disk radiation is comptonized: UV bump --> X (Sikora)

- disk power < jet power ??



Talk Ghisellini

Ultra-Relativistic Jets in Astrophysics

Summary / outlook: AGN / quasar jets

Recent progress in understanding of AGN/quasar jets:

Theory: GR-MHD simulations of disk-jet transition

(Hawley, DeVilliers, Nishikawa, Meier, Mizuno, Kommisarov...)

Special relativistic (M)HD simulations of asymptotic jet

(Mizuta, Ng, Del Zanna, MacFadyen....)

Modeling (jet formation & propagation, radiation)

(Pelletier, Trussoni, Laing, Georganopoulos)

Observ.: Highly resolved X-ray data (Chandra, XMM)

(Hartcastle, Gelbord, Biretta, Marshall, Harris, Croston, Schwartz ...)

Radio (polarisation) modeling (VLBI, VLBA, VLA)

(Gabuzda,Giroletti,Laing,Hardcastle,O'Dowd,Mahmud,Lyutikov,Giovannini)

High energy (TeV) data (HESS)

(Ghisellini, Perlman, Wagner)

Multi-wavelength observations

(Biretta, Mirabel, Ghisellini, Gelbord, Padgett)

Ultra-Relativistic Jets in Astrophysics

Summary / outlook: AGN / quasar jets

Recent progress in understanding of AGN/quasar jets:

Theory: GR-MHD simulations of disk-jet transition
Special relativistic (M)HD simulations of asymptotic jet
Modeling (jet formation & propagation, radiation)

Open questions:

- jet launching by disks (note existence of YSO jets)
  long term evolution, knot formation,
  relativistic speed of GR-MHD jets
- MHD assumption ?
- long term evolution disk / black hole interaction
- Radiative GR-MHD disks / jets
- large-scale jet formation, pc-scale numerical grid
- deliver observationally relavant features
  (intensities, polarization, length scale)
- really only one single scenario of relativistic jet formation ?

Ultra-Relativistic Jets in Astrophysics

Summary / outlook: AGN / quasar jets

Recent progress in understanding of AGN/quasar jets:

Observ.: Highly resolved X-ray data (Chandra, XMM)
Radio polarisation modeling (VLBI, VLBA, VLA)
High energy (TeV) data (HESS)
Multi-wavelength observations

Open questions:

- specific physical input parameters for theory / modeling (densities, velocity, magnetic flux & field geometry)
- jet internal structure: sheat/spine, deceleration, IC-CMB
- Lorentz factors of relativistic jet family: related to what?
- energy carriers: matter or Poynting flux? jet kinetic power ? Radiated power known ...
- similarities to GRBs intriguing, coincidence or physics ?
- disk structure, ADAFs, MDAFs etc .., can P_{jet} be $> P_{accretion}$?
- radio-loud vs quiet: due to M_{out}/M_{in} ? or M_{BH}, or BH spin?